3. Project Technology Options

Chapter Overview

The goal of a landfill gas (LFG) energy project is to convert LFG into a useful energy form, such as electricity, steam, heat, vehicle fuel, or pipeline quality gas. Several technologies can be used to maximize LFG when producing these forms of energy, the most prevalent of which are:

- Power production/cogeneration
- Direct use of medium-British thermal unit (Btu) gas
- Upgrade to vehicle fuel or pipeline-quality (high-Btu) gas

Each of these options has three basic components: a gas collection system and backup flare; a gas treatment system; and an energy recovery system.

The best type of project for a particular landfill will depend upon a number of factors, including existence of an available energy market, project costs, potential revenue sources, and many technical considerations.

This chapter provides a brief overview of the technologies and outlines the major characteristics of energy recovery systems, including the technical issues for determining a project's feasibility related to direct use, power production, and upgrade to vehicle fuel or pipeline quality gas. The chapter concludes with a discussion of how best to choose among the potential energy recovery technologies.

Tables 3-1 and 3-2 show the breakdown of technologies used in LFG electricity and direct-use projects in 2008.

Table 3-1. Technologies for LFG Electricity Projects

Project Technology	Number of Projects*
Internal combustion engine	249
Gas turbine	28
Cogeneration	20
Microturbine	14
Steam turbine	15
Combined cycle	6
Stirling cycle engine	2

* Projects listed as operational in the Landfill Methane Outreach Program (LMOP) database as of October 2008.

Table 3-2. Technologies for Direct-Use Projects

Project Technology	Number of Projects*
Boiler	52
Direct thermal	36
Leachate evaporation	17
High-Btu	15
Greenhouse	4
Alternative fuel (compressed natural gas or liquefied natural gas)	3
Medium-Btu gas injected into natural gas pipeline	1

* Projects listed as operational in the LMOP database as of October 2008.

3.1 Gas Collection System and Flare

Typical LFG collection systems have three central components: collection wells or trenches; a condensate collection and treatment system; and a blower. In addition, most landfills with energy recovery systems include a flare for the combustion of excess gas and for use during equipment downtimes. Each of these components is described below, followed by a brief discussion of collection system and flare costs.

Gas Collection Wells and Horizontal Trenches

Gas collection typically begins after a portion of a landfill (called a cell) is closed.[1] Collection systems can be configured as either vertical wells or horizontal trenches. Some collection systems use a combination of vertical wells and horizontal trenches. Well-designed systems of either type are effective in collecting LFG. The design chosen depends on site-specific conditions and the timing of LFG collection system installation.

Figure 3-1 illustrates the design of a typical vertical LFG extraction well, and Figure 3-2 shows a typical horizontal LFG collection system. Regardless of whether wells or trenches are used, each wellhead is connected to lateral piping, which transports the gas to a main collection header, as illustrated in Figure 3-3. Ideally, the collection system should be designed so that the operator can monitor and adjust the gas flow if necessary.

[1] A proper landfill final cover will allow for a more efficient and effective operation of the LFG collection system.

Figure 3-1. Typical LFG Extraction Well

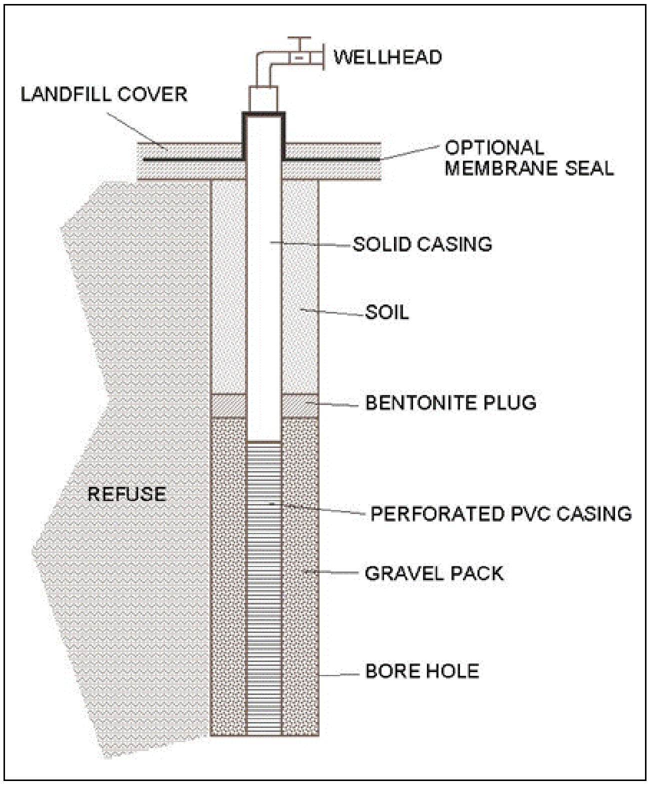


Figure 3-2. Typical LFG Collection System With Horizontal Trenches

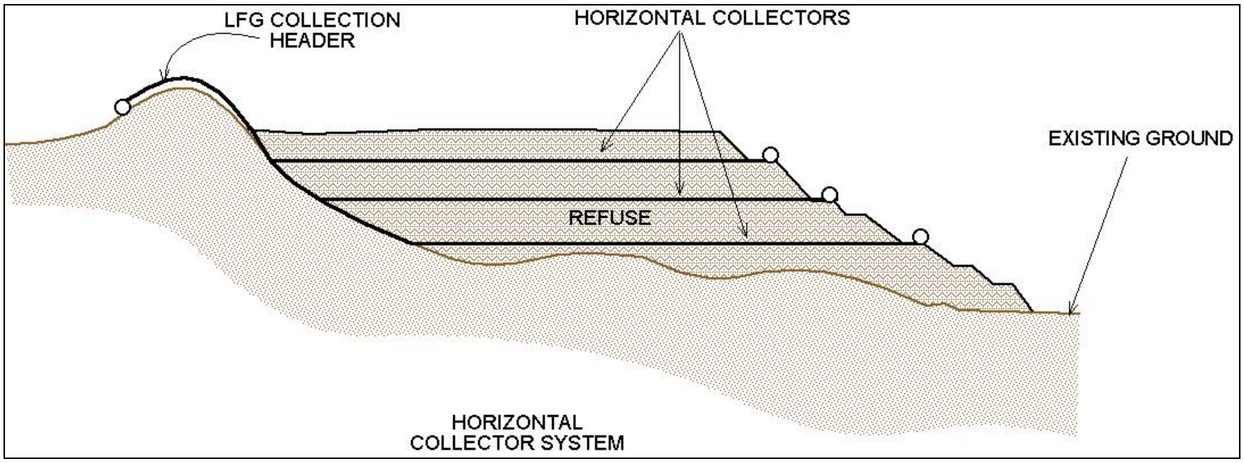
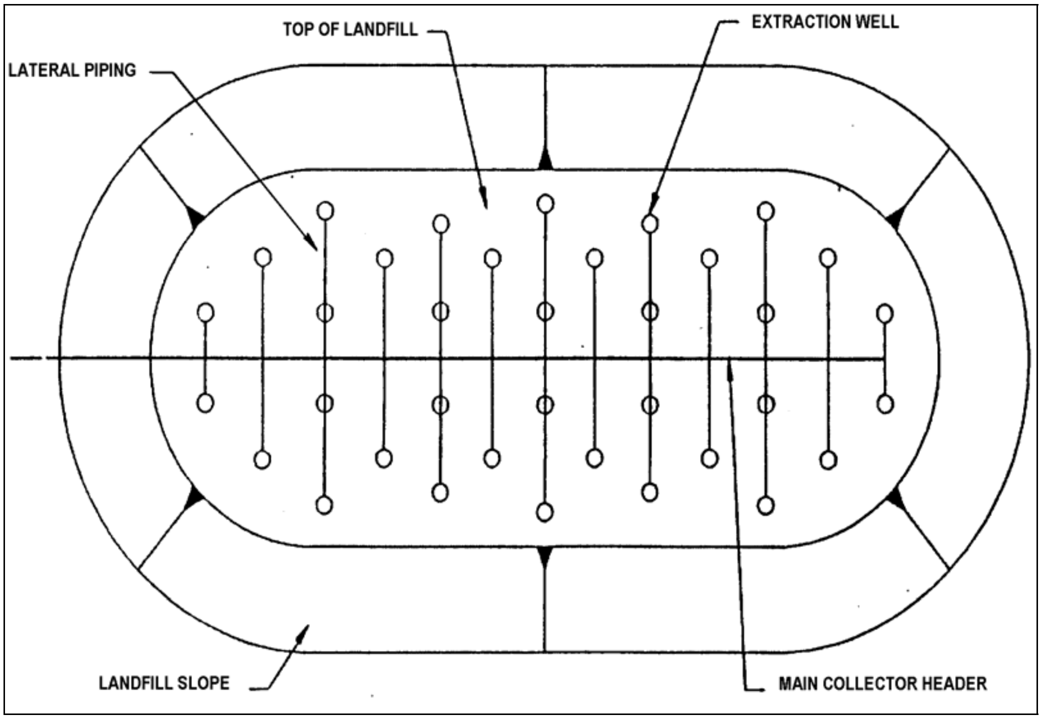


Figure 3-3. Sample LFG Extraction Site Plan



Condensate Collection

Condensate forms when warm gas from the landfill cools as it travels through the collection system. If condensate is not removed, it can block the collection system and disrupt the energy recovery process. Techniques for condensate collection and treatment are described in Section 3.2.

Blower

A blower is necessary to pull the gas from the collection wells into the collection header, and convey the gas to downstream treatment and energy recovery systems. The size, type, and number of blowers needed depend on the gas flow rate and distance to downstream processes.

Flare

A flare is a device for igniting and burning the LFG. Flares are a component of each energy recovery option because they may be needed to control LFG emissions during energy recovery system startup and downtime and to control gas that exceeds the capacity of the energy conversion equipment. In addition, a flare is a cost-effective way to gradually increase the size of the energy recovery system at an active landfill. As more waste is placed in the landfill and the gas collection system is expanded, the flare is used to control excess gas between energy conversion system upgrades (e.g., before addition of another engine).

Flare designs include open (or candlestick) flares and enclosed flares. Enclosed flares are more expensive but may be preferable (or required by state regulations) because they provide greater control of combustion conditions, allow for stack testing, and might achieve slightly higher combustion efficiencies than open flares. They can also reduce noise and light nuisances.

Collection System Costs

Total collection system costs vary widely, based on a number of site-specific factors. For example, if the landfill is deep, collection costs tend to be higher because well depths will need to be increased. Collection costs also increase with the number of wells installed. The estimated capital required for a 40-acre collection system designed for 600 cubic feet per minute (cfm) of LFG (including a flare) is $991,000, approximately $24,000 per acre, assuming one well is installed per acre. Typical annual operation and maintenance (O&M) costs for collection systems are $2,250 per well and $4,500 per flare. Electricity costs to operate the blower for a 600 cfm active gas collection system average $44,500 per year[2]. If an LFG energy project generates electricity, often a landfill will use a portion of the electricity generated to operate the system and sell the rest to a grid in order to offset these operational costs. Flaring costs have been incorporated into these estimated capital and operating costs of LFG collection systems, since excess gas may need to be flared at any time, even if an energy recovery system is installed.

3.2 LFG Treatment Systems

After the LFG has been collected and before it can be used in a conversion process, it must be treated to remove condensate not captured in the condensate removal systems, particulates, and other impurities. Treatment requirements depend on the end use application. The focus of this section is treatment conducted prior to direct-use and electricity projects. Minimal treatment is required for direct use of gas in boilers, furnaces, or kilns. Treatment systems for LFG electricity projects typically include a series of filters to remove contaminants that could damage engine and turbine components and reduce system efficiency.

The more extensive treatment required to produce high-Btu gas for injection into natural gas pipelines or production of alternative fuels is discussed in Section 3.5.

The cost of gas treatment depends on the gas purity requirements of the end use application. The cost of a system to filter the gas and remove condensate for direct use of medium-Btu gas or for electric power production is considerably less than the cost of a system that must also remove contaminates such as siloxane and sulfur that are present at elevated levels in some LFG.

Types of Treatment Systems

Treatment systems can be divided into primary treatment processing and secondary treatment processing. Most primary processing systems include de-watering and filtration to remove moisture and particulates. Dewatering can be as simple as physical removal of free water or condensate in the LFG (often referred to as “knockout” devices). However, it is common in new projects to remove water vapor or humidity in the LFG by using gas cooling and compression. Typical temperatures for

[2] LFGcost-Web V2.0 at http://www.epa.gov/lmop/res/index.htm#5a. September 9, 2009.

gas cooling are from 35 to 50°F. Gas compression is commonly specified by the distance to the energy recovery systems and by their input pressure requirements, and commonly ranges from 10 to over 100 pounds per square inch gauge (psig). These technologies have been in use for many years and are now relatively standard elements of active LFG collection systems. Secondary treatment systems are designed to provide much greater gas cleaning than is possible using primary systems alone. Secondary treatment systems may employ multiple cleanup processes depending on the gas specifications of the end use. Such processes can include both physical and chemical treatments.

The type of secondary treatment depends on the constituents that need to be removed for the desired end use. Two of the trace contaminants that may have to be removed from LFG are:

- *Siloxanes:* Siloxanes are found in household and commercial products that find their way into solid waste and wastewater (a concern for landfills that take wastewater treatment sludge). The siloxanes in the landfill volatilize into the LFG and are converted to silicon dioxide when the LFG is combusted. Silicon dioxide (the main constituent of sand) is a white substance that collects on the inside of the internal combustion engine and gas turbine components and on boiler tubes, potentially reducing the performance of the equipment and resulting in significantly higher maintenance cost. The need for siloxane treatment depends on the level of siloxane in the LFG (which varies among landfills) and on manufacturer recommendations for the energy technology selected.

- *Sulfur compounds:* These compounds, which include sulfides/disulfides (e.g., hydrogen sulfide), are corrosive in the presence of moisture.

The most common technologies used for secondary treatment are adsorption and absorption. Adsorption involves the physical adsorption of the contaminant onto the surface of an adsorbent such as activated carbon or silica gel. Adsorption has been a common technology for removing siloxanes from LFG. Absorption (or scrubbing) involves the chemical/physical reaction of a contaminant with a solvent or solid reactant. Absorption has been a common technology for removing sulfur compounds from LFG.

Advanced treatment technologies that remove carbon dioxide, non-methane organic compounds (NMOCs), and a variety of other contaminants in LFG to produce a high-Btu gas (typically at least 96 percent methane) are discussed in Section 3.5.

3.3 Electricity Generation

Producing electricity from LFG continues to be the most common beneficial use application, accounting for about two-thirds of all U.S. LFG energy projects. Electricity can be produced by burning LFG in an internal combustion engine, a gas turbine, or a microturbine. Each of the following subsections describes one of these technologies, suggests its advantages and disadvantages, and provides some cost guidance.

Internal Combustion Engines

The internal combustion engine, shown in Figure 3-4, is the most commonly used conversion technology in LFG applications; more than 70 percent of all existing LFG electricity projects use them. The reason for such widespread use is their relatively low cost, high efficiency, and good size match with the gas output of many landfills. Internal combustion engines have generally been used at sites where gas quantity is capable of producing 800 kilowatts (kW) to 3 megawatts (MW), or where sustainable LFG flow rates to the engines are approximately 0.4 to 1.6 million cubic feet per day (cfd) at 50 percent methane. Multiple engines can be combined together for projects larger than 3 MW.

Figure 3-4. Internal Combustion Engines

Table 3-3 provides examples of available sizes of internal combustion engines.

Table 3-3. Internal Combustion Engine Sizes

Engine Size	Gas Flow (in cfm at 50% Methane)
540 kW	204
633 kW	234
800 kW	350
1.2 MW	500

cfm: cubic feet per minute

Internal combustion engines are relatively efficient at converting LFG into electricity, achieving efficiencies in the range of 25 to 35 percent. Even greater efficiencies are achieved in combined heat and power (CHP) applications where waste heat is recovered from the engine cooling system to make hot water, or from the engine exhaust to make low-pressure steam. For more information about CHP, which can be used with internal combustion engines, turbines, or microturbines, see the CHP Partnership's Biomass CHP Catalog of Technologies and the Catalog of CHP Technologies.

The following case studies developed by LMOP provide examples of a large (i.e., 10 MW) and an average size (i.e., 3-4 MW) internal combustion engine project:

- Green Knight Energy Development Project (10 MW)
- Dairyland LFG Energy Project (4 MW)

Gas Turbines

Gas turbines, shown in Figure 3-5, are typically used in larger LFG energy projects, where LFG volumes are sufficient to generate a minimum of 3 MW, and typically more than 5 MW (i.e., where gas flows exceed a minimum of 2 million cfd). This technology is competitive in larger LFG electric generation projects because, unlike most internal combustion engine systems, gas turbine systems have significant economies of scale. The cost per kW of generating capacity drops as gas turbine size increases, and the electric generation efficiency generally improves as well.

Figure 3-5. Gas Turbines

Simple-cycle gas turbines applicable to LFG energy projects typically achieve efficiencies of 20 to 28 percent at full load; however, these efficiencies drop substantially when the unit is running at partial load. Combined-cycle configurations, which recover the waste heat in the gas turbine exhaust to make additional electricity, can boost the system efficiency to approximately 40 percent, but this configuration is also less efficient at partial load. A primary disadvantage of gas turbines is that they require high gas compression (165 psig or greater), causing high parasitic load loss. This means that more of the plant's power is required to run the compression system, compared to other generator options. Advantages of gas turbines are that they are more resistant to corrosion damage than internal combustion engines and have lower nitrogen oxides emission rates. In addition, gas turbines are relatively compact and have low O&M costs compared to internal combustion engines. However, LFG treatment for the removal of siloxanes may be required to meet manufacturer specifications.

> An example of a gas turbine project is at the Arlington Landfill in Arlington, Texas where LFG is piped four miles to the Arlington Wastewater Treatment Plant and used to fuel two 5.2 MW gas turbine generators.

Microturbines[3]

Microturbines (Figure 3-6) have been sold commercially in landfill and other biogas applications since early 2001. In general, microturbine project costs have been more expensive on a dollar-per-kW installed capacity basis than internal combustion engine projects. Some of the reasons projects have selected microturbine technology instead of internal combustion engines include:

- LFG availability at less than the 300 cfm required for typical internal combustion engines (although recently, small internal combustion engines have become available in this size range).
- Lower percent methane as microturbines can function with as little as 35 percent methane.
- Low nitrogen oxides emissions desired.
- Ability to add and remove microturbines as available gas quantity changes.
- Relatively easy interconnection due to lower generation capacity.

Figure 3-6. Microturbine

In earlier microturbine applications, LFG was not treated sufficiently; this resulted in system failures. Typically, LFG treatment to remove moisture, siloxanes, and other contaminants is required for microturbines. Treatment includes the following components:

- Inlet moisture separator.
- Rotary vane type compressor.
- Chilled water heat exchanger (reducing LFG temperature to 40°F).
- Coalescing filter.

[3] Wang, Benson, Wheless. 2003. *Microturbine Operating Experience at Landfills.* SWANA 26th Annual Landfill Gas Symposium (2003), Tampa, Florida.

- LFG reheat exchanger (to add 20 to 40ºF above dew point).

- Further treatment of the moisture-free LFG in vessels charged with activated carbon and/or other media (optional).

Microturbines come in sizes of 30, 70, and 250 kW. Projects should use the larger-capacity microturbines where power requirements and LFG availability can support them. The following benefits can be gained by using a larger microturbine:

- Reduced capital cost (on a dollar-per- kW of installed capacity basis) for the microturbine itself.

- Reduced maintenance cost.

- Reduced balance of plant installation costs — a reduction in the number of microturbines to reach a given capacity will reduce piping, wiring, and foundation costs.

- Improved efficiency — the heat rate of the 250 kW microturbine is expected to be about 3.3 percent better than the 70 kW and about 12.2 percent better than the 30 kW microturbine.

An example of a microturbine project is the Lopez Canyon LFG Energy Project.

Electricity Generation Cost Summary

The costs of energy generation using LFG vary greatly; they depend on many factors including the type of electricity generation equipment, its size, the necessary compression and treatment system, and the interconnect equipment. Table 3-4 presents examples of typical costs for several technologies, including costs for a basic gas treatment system typically used with each technology.

Table 3-4. Examples of Typical Costs

Technology	Typical Capital Costs ($/kW)*	Typical Annual O&M Costs ($/kW)*
Internal combustion engine (> 800 kW)	$1,700	$180
Small internal combustion engine (< 1 MW)	$2,300	$210
Gas turbine (> 3 MW)	$1,400	$130
Microturbine (< 1 MW)	$5,500	$380

* 2010 dollars.
kW: kilowatt
MW: megawatt

A growing problem for all electricity generation projects is the accumulation of siloxanes. Before an LFG electric generation project is installed, the LFG should be tested to determine the level of siloxanes present. Even electric generation projects that have been operating without a siloxane issue may one day encounter problems if the levels of siloxanes in the landfill and the LFG increase. Depending on the level of siloxanes, gas treatment is required before LFG is introduced to the electricity generating equipment. The most common type of treatment is activated carbon filtration (adsorption), although other adsorption media, such as silica gel, are being tested. Subzero refrigeration and liquid scrubbing are other gas treatment technologies that can remove siloxanes.

3.4 Direct Use of Medium-Btu Gas

Boilers, Dryers, and Kilns

The simplest and often most cost-effective use of LFG is as a medium-Btu fuel for boiler or industrial process use (e.g., drying operations, kiln operations, and cement and asphalt production). In these projects, the gas is piped directly to a nearby customer where it is used in new or existing combustion equipment (see Figure 3-7) as a replacement or supplementary fuel. Only limited condensate removal and filtration treatment is required, but some modifications of existing combustion equipment might be necessary.

Because of the cost of natural gas, this technology has gained popularity in recent years. The economics of longer pipelines have become more favorable. For more cost information see Chapter 4.

The energy users' energy requirements are an important consideration when evaluating the sale of LFG for direct use. Because no economical way to store LFG exists, all gas that is recovered must be used as available, or it is essentially lost, along with associated revenue opportunities. The ideal gas customer, therefore, will have a steady annual gas demand compatible with the landfill's gas flow. When a landfill does not have adequate gas flow to support the entire needs of a facility, LFG can still be used to supply a portion of the needs. For example, in some facilities, only one piece of equipment (e.g., a main boiler) or set of burners is dedicated to burning LFG. These facilities might also have equipment that can use LFG along with other fuels. Other facilities blend LFG with other fuels.

Figure 3-7. Boiler and Cement Kiln

Table 3-5 gives the expected annual gas flows on a million Btu (MMBtu) per year basis from landfills of different sizes. While actual gas flows will vary based on waste age, composition, moisture, and other factors, these numbers can be used as a first step toward determining the compatibility of customer gas requirements and LFG output. A rule of thumb for comparing boiler fuel requirements to LFG output is that approximately 8,000 to 10,000 pounds per hour of steam can be generated for every 1 million metric tons of waste-in-place at a landfill; accordingly, a 5 million metric ton landfill can support the needs of a large facility requiring about 50,000 pounds per hour of steam for process use. Prior to pursuing a LFG energy direct-use project, however, LFG flow should be measured and/or gas modeling should be conducted as described in Chapter 2, to refine the estimate of LFG flow and energy available from the landfill.

Table 3-5. LFG Flows Based on Landfill Size

Landfill Size (Metric Tons Waste-in-Place)	LFG Output (MMBtu/yr)	Steam Flow Potential (lbs/hr)
1,000,000	100,000	10,000
5,000,000	450,000	45,000
10,000,000	850,000	85,000

MMBtu/yr: million Btu per year

If an ideal customer is not accessible, it may be possible to create a steady gas demand by serving multiple customers whose gas requirements are complementary. For example, an asphalt producer's summer gas load could be combined with a municipal building's winter heating load to create a year-round demand for LFG.

Equipment modifications or adjustments may be necessary to accommodate the lower Btu value of LFG, and the costs of modifications will vary. If retuning the boiler burner is the only modification required, costs will be minimal.

The costs associated with retrofitting boilers will vary from unit to unit depending on boiler type, fuel use, and age of unit. Typical tiers of retrofits include:

- Incorporation of LFG in a unit that is co-firing with other fuels, where automatic controls are required to sustain a co-firing application or to provide for immediate and seamless fuel switching in the event of a loss in LFG pressure to the unit. This retrofit will ensure uninterruptible steam supply. Overall costs can range from $200,000 to $400,000 and include all retrofit costs (burner modifications, fuel train, process controls).

- Modification of a unit where surplus or back-up steam supply is available and uninterruptible steam supply from the unit is not required if loss of LFG pressure to the unit occurs. In this case, manual controls are implemented and the boiler operating system is not integrated in an automatic control system. Overall costs can range from $100,000 to $200,000.

Another option is to improve the quality of the gas to such a level that the boiler will not require a retrofit. The gas is not required to have a Btu value as high as pipeline-quality, but the quality must be between medium and high. This option reduces the cost of a boiler retrofit and subsequent maintenance costs associated with cleaning because of deposits associated with use of medium-Btu LFG.

A potential problem for boilers is the accumulation of siloxanes. The presence of siloxanes in the LFG causes a white substance to build up on the boiler tubes. Operators who experience this problem typically choose to perform routine cleaning of the boiler tubes. Boiler operators may also choose to install a gas treatment system, such as those discussed in Section 3.2, to reduce the amount of siloxanes in the LFG prior to delivery to the boiler.

For more information about the use of LFG in boilers, see the LMOP fact sheet on boilers.

A case study of a boiler adaptation at the NASA Goddard Flight Center also provides information about LFG use in boilers.

The following case study examples of direct thermal projects can be found on LMOP's Web site:

- Kilns
  St. John's LFG Energy Project
- Dryers
  Clay Mine LFG Application
  Buncombe County Sludge Drying Project
- Process Heaters
  Wayne Township LFG Energy Project for Jersey Shore Steel

Infrared Heaters

Infrared heating using LFG (Figure 3-8) is ideal when a facility with space heating needs is located near a landfill. Infrared heating creates high-intensity energy that is safely absorbed by surfaces that warm up. In turn, these surfaces release heat into the atmosphere and raise the ambient temperature. Infrared heating, using LFG as a fuel source, has been successfully employed at several landfill sites in Europe, Canada, and the United States. Infrared heaters require a small amount of LFG to operate and are relatively inexpensive and easy to install. Current operational projects use between 20 and 50 m^3/hr (12 to 30 cfm). Infrared heaters do not require pretreatment of the LFG, unless there are siloxanes in the gas.

The cost of infrared heaters depends on the area to be heated. One heater is needed for every 500 to 800 square feet. The cost of each heater, in 2007 dollars, is approximately $3,000. In addition, the cost of the interior piping to connect the heaters within the building ceilings is approximately $20,000 to $30,000.

An example of the use of infrared heaters in maintenance facilities is at I-95 Landfill in Virginia.

Figure 3-8. Infrared Heaters

Greenhouses

Greenhouses are another application for LFG (Figure 3-9). LFG can be used to provide heat for greenhouses and also to heat water used in hydroponic plant culture. LFG can be used in a microturbine to power the grow lights and the waste heat can be used for heating the greenhouse or water.

Figure 3-9. Greenhouse

> Several greenhouses have been constructed near landfills in order to take advantage of the energy cost savings, for example at the Rutgers University EcoComplex Greenhouse.

The costs related to using LFG in greenhouses depend on how the LFG will be used. If the grow lights are powered by a microturbine, then the project costs would be similar to an equivalent microturbine

LFG energy project. If LFG is used to heat the greenhouse, the cost incurred would be the cost of the piping and of the technology used, such as boilers. See the appropriate technology section in this chapter and Chapter 4 for cost information.

Artisan Studios

Artisan studios with energy-intensive activities such as glass-blowing, metalworking, and pottery Figure 3-10) offer another opportunity for the beneficial use of LFG. This application does not require a large amount of LFG and can be coupled with a commercial project. For example, a gas flow of 100 cfm is sufficient for a studio that houses glass-blowing, metalworking, or pottery.

> The first artisan project to use LFG was at the EnergyXchange at the Yancey-Mitchell Landfill in North Carolina. At this site, LFG is used to power two craft studios, four greenhouses, a gallery, and a visitor center.

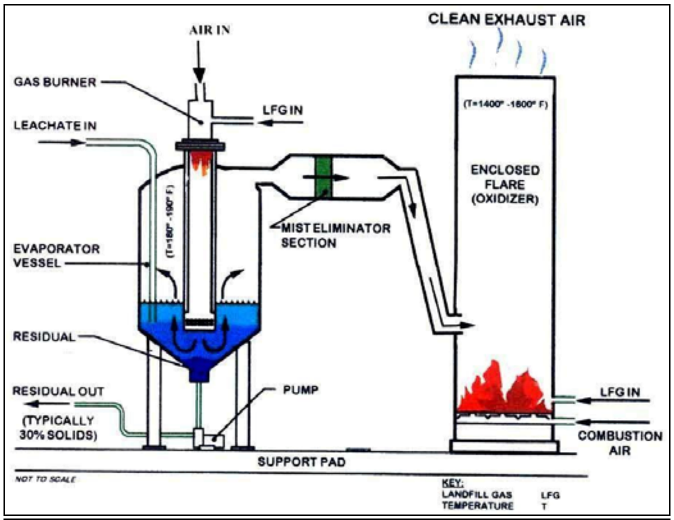
Figure 3-10. LFG-Powered Glass Studio

Leachate Evaporation

Leachate evaporation (Figure 3-11) is a good option for landfills where leachate disposal in a publicly owned treatment works (POTW) plant is unavailable or expensive. Evaporators are available in sizes to treat 10,000 to 30,000 gallons per day (gpd) of leachate. LFG is used to evaporate leachate to a more concentrated and more easily disposed effluent volume. Capital costs range from $300,000 to $500,000. O&M costs range from $70,000 to $95,000 per year. When a system is owned and operated by a third party, long term contracts will typically assess costs based on the volume of leachate evaporated. Some economies of scale are realized for larger size vessels. A 30,000 gpd evaporator costs $.05 - $.06 per gallon, while a 20,000 gpd unit is $.09 - $.12 per gallon and a 10,000 gpd unit is $.18 - $.20 per gallon.

> The Olympic View Landfill in Port Orchard, Washington, uses leachate evaporation.

Figure 3-11. Leachate Evaporation Diagram and Photo



Biofuel Production

LFG can be used to heat the boilers in plants that produce biofuels including biodiesel and ethanol. In this case, LFG is used directly as a fuel to offset another fossil fuel. Alternatively, LFG can be used as feedstock when it is converted to methanol for biodiesel production.

> One example of such a project is located in Denton, Texas. The City of Denton collects used vegetable oil and processes it, using LFG as a fuel source, to produce biodiesel to operate its vehicle fleet.

3.5 Conversion to High-Btu Gas[4]

LFG can be used to produce the equivalent of pipeline-quality gas (natural gas), compressed natural gas (CNG), or liquefied natural gas (LNG). Pipeline-quality gas can be sold into a natural gas pipeline used for an industrial purpose. CNG and LNG can be used to fuel vehicles at the landfill (e.g., water trucks, earthmoving equipment, light trucks, autos), fuel refuse-hauling tucks (long haul refuse transfer trailers and route collection trucks), and supply the general commercial market (Figure 3-12). Recent capital costs of high-Btu processing equipment have ranged from $2,600 to $4,300 per standard cubic foot per minute (scfm) of LFG. The annual cost to provide electricity to, operate, and maintain these systems ranges from $875,000 to $3.5 million.[5] Costs will depend on the purity of the high-Btu gas required by the receiving pipeline or energy end user as well as the size of the project, since some economies of scale can be achieved when producing larger quantities of high-Btu gas.

[4] Pierce, J. SCS Engineers. 2007. *Landfill Gas to Vehicle Fuel: Assessment of Its Technical and Economic Feasibility.* SWANA 30th Annual Landfill Gas Symposium (March 4 to 8, 2007), Monterey, California.
[5] LFGcost-Web V2.0 at http://www.epa.gov/lmop/res/index.htm#5a. September 9, 2009.

Figure 3-12. LNG-Powered Trucks and LNG Station

LFG can be converted into a high-Btu gas by increasing its methane content and, conversely, reducing its carbon dioxide, nitrogen, and oxygen content. In the United States, three methods have been commercially employed (i.e., beyond pilot testing) to remove carbon dioxide from LFG:

- Membrane separation
- Molecular sieve (also known as pressure swing adsorption or PSA)
- Amine scrubbing

All three methods focus on removing carbon dioxide, not oxygen or nitrogen. The preferred method to reduce the level of oxygen and nitrogen in LFG to pipeline specifications is to design and operate the gas collection system (wellfield) properly. The primary cause for the presence of oxygen and nitrogen in LFG is air intrusion: LFG collection systems create a vacuum, and air can be drawn through the surface of the landfill and into the gas collection system. Air intrusion can often be minimized by adjusting well vacuums and repairing leaks in the landfill cover. In some instances, air intrusion can be managed by sending LFG from the interior wells directly to the high-Btu process, and sending LFG from the perimeter wells (which often have higher nitrogen and oxygen levels) to another beneficial use or emissions control device.

Membrane separation can achieve some incidental oxygen removal, but nitrogen — which represents the bulk of the non-methane/non-carbon dioxide fraction of LFG — is not removed. A molecular sieve can be configured to remove nitrogen by proper selection of media. Nitrogen removal, in addition to carbon dioxide removal requires a two-stage molecular sieve (PSA).

Amine Scrubbing Process. Selexol has been the most common amine used in amine scrubbing systems to convert LFG to high-Btu gas. A typical Selexol-based plant employs the following steps:

- LFG compression (using electric drive, LFG-fired engine drive, or product gas–fired engine drive).
- Moisture removal using refrigeration.
- Hydrogen sulfide removal in a solid media bed (using an iron sponge or a proprietary media).
- NMOC removal in a primary Selexol absorber.
- Carbon dioxide removal in a secondary Selexol absorber.

In a Selexol absorber tower, the LFG is placed in contact with the Selexol liquid. Selexol is a physical solvent that preferentially absorbs gases into the liquid phase. NMOCs are generally hundreds to thousands of times more soluble than methane. Carbon dioxide is about 15 more times soluble than methane. Solubility also is enhanced with pressure, facilitating the separation of NMOCs and carbon dioxide from methane.

Molecular Sieve Process. A typical molecular sieve plant employs the compression, moisture removal, and hydrogen sulfide removal steps listed under the amine scrubbing process, but relies on vapor phase activated carbon and a molecular sieve for NMOC and carbon dioxide removal, respectively. Once the activated carbon is exhausted, it can be regenerated on site through a depressurizing heating and purge cycle. The process is known as thermal swing absorption.

Membrane Separation Process. A typical membrane plant employs compression, moisture removal, and hydrogen sulfide removal steps, but relies upon activated carbon to remove NMOCs and membranes to remove carbon dioxide. Activated carbon removes NMOCs and protects the membranes. The membrane process exploits the fact that gases, under the same conditions, will pass through polymeric membranes at differing rates. Carbon dioxide passes through the membrane approximately 20 times faster than methane. Pressure is the driving force for the separation process. Early membrane plants used “high” pressure membranes. Newer plants use “low” pressure membranes.

An example of a pipeline-quality gas project is the one in City of Fort Smith, Arkansas.

CNG

For CNG production, the membrane separation and molecular sieve processes scale down more economically to smaller plants. For this reason, these technologies are more likely to be used for CNG production than the Selexol (amine scrubbing) process.

The Los Angeles County Sanitation District's LFG to CNG project at Puente Hills Landfill has been operating for more than 10 years. It converts an inlet flow of 250 scfm at 55 percent methane to 100 scfm of CNG at 96 percent methane. The product is equivalent to about 1,000 gallons of gasoline equivalent per day. At a fuel economy of 20 miles per gallon, the facility can support about 20,000 trip miles per day.

The process chain for CNG production at Puente Hills is as follows:

- LFG compression and moisture removal. Compression is undertaken in multiple stages to reach 525 psi.
- Vapor phase activated carbon.
- Gas heating to 140°F.
- Three stages of membrane separation.
- Multi-stage compression of the product gas to 3,600 psi.
- Compressed gas storage facilities.
- A fuel dispenser to dispense 3,000 psi CNG.

Construction of the Puente Hills CNG facility cost $1.8 million (cost escalated to 2007 dollars). The Puente Hills project is a relatively small demonstration project and its cost is therefore not representative of a larger project.[6] Table 3-6 shows estimated total costs of CNG production for membrane separation processes capable of handling various gas flows.

Table 3-6. Cost of CNG Production*

Inlet LFG (scfm)	Plant Size (GGE/day)	Cost ($/GGE)
250	1,000	$1.40
500	2,000	$1.13
1,250	5,000	$0.91
2,500	10,000	$0.82
5,000	20,000	$0.68

* Costs escalated to 2007 dollars from Wheless, E., et al. 1994. "Processing and Utilization of Landfill Gas as a Clean Alternative Vehicle Fuel." SWANA 17th Annual Landfill Gas Symposium (March 22 to 24, 1994), Long Beach, CA.

GGE: gallons of gasoline equivalent
scfm: standard cubic feet per minute

More information about the Puente Hills CNG project is available on LMOP's Web site.

[6] Pierce, J. SCS Engineers. 2007. *Landfill Gas to Vehicle Fuel: Assessment of Its Technical and Economic Feasibility*. SWANA 30th Annual Landfill Gas Symposium (March 4 to 8, 2007), Monterey, California.

LNG

If LFG is first converted to CNG, it can then be liquefied to produce LNG using conventional natural gas liquefaction technology. When considering this technology, two factors must be considered:

- Carbon dioxide freezes at a temperature higher than methane liquefies. To avoid "icing" in the plant, the product CNG must have as low a level of carbon dioxide as possible. This low carbon dioxide requirement would favor the molecular sieve over the membrane process, or at least favor upgrading the gas produced by the membrane process with a molecular sieve.

- Natural gas liquefaction plants have generally been "design to order" facilities that process large quantities of LNG. A few manufacturers have begun offering smaller, pre-packaged liquefaction plants. Even these "small" plants have design capacities of 10,000 gallons/day or greater.

Unless the nitrogen and oxygen content of the LFG is very low, the process chain must include nitrogen and oxygen removal steps. Liquefier manufacturers desire an inlet gas to have less than 0.5 percent oxygen, citing explosion concerns. Nitrogen needs to be limited to obtain the desired LNG methane content of 96 percent.

The cost of LNG production is estimated to be $0.65/gallon for a plant producing 15,000 gallons/day of LNG. A plant producing 15,000 gallons/day of LNG requires 3,000 scfm of LFG and would require a capital investment approaching $20 million.[7]

3.6 Selection of Technology

The primary factor in choosing the right project configuration for a particular landfill is the projected expense versus potential revenue. In general, sale of medium-Btu gas to a nearby customer, which requires minimal gas processing and typically is tied to a retail gas rate rather an electric buyback rate, is the simplest and most cost-effective option. If a suitable customer is located nearby and is willing to purchase the gas, this option should be thoroughly examined. An energy user that requires gas 24 hours per day, 365 days a year, is the best match for an LFG energy project, since intermittent or seasonal LFG uses typically result in the wasting of gas during the off-periods. If no such customer exists, the landfill could use its energy resources to attract industry to locate near the landfill. The landfill should work with a local department of economic development to develop a strategy for this option.

> Some corporations are deciding to build facilities near landfills in order to take advantage of LFG as a reliable, renewable fuel that costs less than natural gas. An example is when Jenkins Brick decided to locate a new plant near the Veolia ES Star Ridge Landfill in Moody, Alabama.

[7] Pierce, J. SCS Engineers. 2007. *Landfill Gas to Vehicle Fuel: Assessment of Its Technical and Economic Feasibility.* SWANA 30th Annual Landfill Gas Symposium (March 4 to 8, 2007), Monterey, California.

Electricity generation may prove to be the best option if no nearby energy user can be found. The economics of an electric generation project depend largely on factors including the price at which the electricity can be sold, available tax credits, or other revenue streams such as renewable energy credits and carbon credits. If the purchasing utility pays only the avoided cost[8] for the electricity and no other revenue streams are available, an electric generation project may not be economically feasible. Fortunately, with the interest in renewable energy and the growing numbers of states with Renewable Portfolio Standards (RPS), electric generation projects are receiving better than avoided cost power purchase agreements (PPA).[9]

In addition to a favorable sales agreement (e.g., PPA) with the purchaser of the electricity, negotiating an acceptable interconnection agreement is important to a successful electric generation project. The interconnection agreement can be a large cost variable, and discussions with the utility should therefore begin early in the project.

If an electric generation project is selected, the next step is to choose the type of power generation. The preferred generator type depends on the amount of recoverable LFG, the expected quantity for at least 10 years, and the gas quality. If both heat or steam and electric power are needed forms of energy, then a CHP project may be the appropriate choice. Regardless of which generator type is used, the project will most likely need to be sized smaller than the amount of available gas to ensure full-load operation of equipment. Therefore the project likely will have excess gas that will have to be flared.

State and local air quality regulations and limits can also play a role in technology selection. Refer to local air regulations for determining restrictions on technologies. For example, internal combustion engines may not be able to comply with nitrogen oxides emission requirements and a gas turbine or microturbine may need to be used. Even gas turbines may require more extensive pretreatment of the gas and/or exhaust treatment to meet stringent emission limits for various pollutants.

Regions of the country with more stringent air regulations offer opportunities for an LFG to CNG or LNG project, because use of these fuels in landfill vehicles or refuse collection and transfer fleets in place of fossil fuels will lower emissions from these vehicles.

Table 3-7 shows a summary of the different LFG energy technologies discussed in this chapter. The table presents key advantages and disadvantages associated to each technology. It also shows the amount of LFG flow usually associated with each technology. For technology costs, which are also an important factor in selecting a technology, see Chapter 4.

[8] Avoided costs are the costs the utility avoids, or saves, by not making the equivalent amount of electricity in one of their own facilities, and would include fuel costs and some operating costs, but not fixed costs.

[9] The most traditional and historically common structure for an LFG electricity project is to sell the electricity to an investor-owned utility (IOU), cooperative, or municipal entity through a PPA. Typically, the electricity, including energy and capacity, is sold to the IOU at a fixed price with some kind of escalation, or an indexed price based on an estimate of short run avoided cost, or a publicly available local market price mechanism. (See Chapter 5 for more information.)

Table 3-7. Summary of LFG Energy Technologies

Project	Technology	Advantages	Disadvantages	LFG Flow Range for Typical Projects (at Approx. 50% Methane)
Electricity	Internal combustion engine Sizing: 800 kW to 3 MW per engine	High efficiency compared to gas turbines and microturbines. Good size match with the gas output of many landfills. Relatively low cost on a per kW installed capacity basis when compared to gas turbines and microturbines. Efficiency increases when waste heat is recovered. Can add/remove engines to follow gas recovery trends.	Relatively high maintenance costs. Relatively high air emissions. Economics may be marginal in areas of the country with low electricity costs.	300 to 1,100 cfm; multiple engines can be combined for larger projects
	Gas turbine Sizing: 1 to 10 MW per gas turbine	Economies of scale, since the cost of kW of generating capacity drops as gas turbine size increases and the efficiency improves as well. Efficiency increases when heat is recovered. More resistant to corrosion damage. Low nitrogen oxides emissions. Relatively compact.	Efficiencies drop when the unit is running at partial load. Require high gas compression. High parasitic loads. Economics may be marginal in areas of the country with low electricity costs.	Exceeds minimum of 1,300 cfm; typically exceeds 2,100 cfm
	Microturbine Sizing: 30 to 250 kW per microturbine	Need lower gas flow. Can function with lower percent methane. Low nitrogen oxides emissions. Relatively easy interconnection. Ability to add and remove units as available gas quantity changes.	Require fairly extensive pre-treatment of LFG. Economics may be marginal in areas of the country with low electricity costs.	20 to 200 cfm

Table 3-7. Summary of LFG Energy Technologies

Project	Technology	Advantages	Disadvantages	LFG Flow Range for Typical Projects (at Approx. 50% Methane)
Direct Use Medium-Btu	Boiler, dryer, and process heater	Can utilize maximum amount of recovered gas flow. Cost-effective. Limited condensate removal and filtration treatment is required. Gas can be blended with other fuels.	Need to retrofit equipment or improve quality of gas. All recovered gas must be used or it is lost. Cost is tied to length of pipeline; energy user must be nearby.	Utilizes all available recovered gas
	Infrared heater	Limited condensate removal and filtration treatment is required. Relatively inexpensive. Easy to install. Does not require large amount of gas. Can be coupled with another energy project.	Seasonal use may limit LFG utilization.	Small quantities of gas, as low as 20 cfm
	Greenhouse	Can mix different technologies.	Seasonal use may limit LFG utilization.	Small quantities of gas
	Artisan studio	Does not require large amount of gas. Can be coupled with a commercial project.	Project economics may be limited without grant or other outside funding sources.	Small quantities of gas
	Leachate evaporation	Good option for landfill where leachate disposal is expensive.	High capital costs.	1,000 cfm is necessary to treat 1 gallon per minute of leachate
Direct Use High-Btu	Pipeline-quality gas	Can be sold into a natural gas pipeline.	Requires potentially expensive gas processing. Increased cost due to tight management of wellfield operation needed to limit oxygen and nitrogen intrusion into LFG.	600 cfm and up, based on currently operating projects
	CNG or LNG	Alternative fuels for vehicles at the landfill or refuse hauling trucks, and for supply to the general commercial market.	Requires potentially expensive gas processing. Increased cost due to tight management of wellfield operation needed to limit oxygen and nitrogen intrusion into LFG.	Dependent on project-specific conditions